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Ionospheric Measurements from NAVSTAR Satellites

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Richard L. Johns

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Director of Operational Applications

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

For several months, three Navstar satellites have been extensively tracked by monitor stations located in California, Alaska, Hawaii, and Guam. As part of this tracking process, data was acquired which is a measure of the ionospheric delay encountered by the navigation signal from the satellites. This report describes the measurement techniques used at the monitor stations, the data obtained from these measurements, and the methods used to compute ionospheric delay. Typical plots of this delay for the various combinations of monitor stations and satellites are presented.

CONTENTS

FIGURES

FIGURES (Continued)

TABLE

I. INTRODUCTION

The Navstar/Global Positioning System (GPS) is a satellite-based navigation system that provides extremely accurate three-dimensional position and velocity information to properly equipped users anywhere on or near the earth. It is a Joint Service Program, managed by the Air Force with deputies from the Navy, Army, Marines, Defense Mapping Agency, and Coast Guard and with technical support provided by The Aerospace Corporation. The baseline program is divided into three phases:

I - Concept Validation Phase (1974-1979)
II - System Validation Phase (1979-1983)
III - Production Phase (1983-1987)

The major elements comprising the navigation payload on the satellites are the pseudo random noise signal assembly (PRNSA), atomic frequency standard, processor, and L-band antenna. The PRNSA includes the baseband generator, which produces the basic P (precise) and C/A (coarse/acquisition) ranging codes and encodes navigation data from the processor onto the pseudo random noise ranging signal; the amplifier/modulator units that supply the L_1 (1575.42 MHz) and L_2 (1227.6 MHz) carrier frequencies modulated by the PRN ranging signals; and the high-power amplifiers that amplify the carrier signals for transmission.

The user segment measures pseudo range and pseudo range rate using the navigation signal from each of four satellites. (Pseudo range is the true distance from the satellite to the user plus an offset due to the user's clock bias. Similarly, pseudo range rate is the true slant range rate plus an offset due to the frequency of the user's clock.) Each signal carries ephemeris data and system timing information for that satellite, which allows the user receiver/processor to convert the pseudo range and pseudo range rate to user three-dimensional position and velocity.

The control segment consists of a Master Control Station (MCS), a navigation message upload station, and widely separated monitor stations. The monitor stations passively track all satellites in view and accumulate ranging data, which is processed at the MCS to calculate the satellite ephemerides and clock offsets. At least once a day this information is transmitted by the upload station to the satellites for subsequent downlink transmission of the navigation data encoded on the carrier signals.

Under contract to the Space and Missile Systems Organization (SAMSO) of the U.S. Air Force, the Navstar satellites were developed and produced by Rockwell International Corp., Seal Beach, Calif. Magnavox Government and Industrial Electronics Co., Torrance, Calif., has developed a variety of user equipments, including the receivers now being used at the monitor stations. General Dynamics, Electronics Division, San Diego, Calif., which is responsible for the control segment, provided magnetic data tapes used in the preparation of this report.

II. TYPICAL RESULTS

There are two methods for obtaining the ionospheric delay. A direct ionospheric delay measurement is accomplished by the use of two carrier frequencies, L_1 (1575.42 MHz) and L_2 (1227.6 MHz). Both carrier frequencies are biphase modulated by a pseudo random noise (PRN) ranging signal. A measurement of the differences in range at the two frequencies is made and, since the ionospheric delay is inversely proportional to the square of the carrier frequency, the absolute ionospheric delay at each of these two frequencies is readily obtained. The second method takes advantage of the opposite effect of the ionosphere on the PRN modulation and the carrier. The ionosphere causes a "group delay" of the PRN modulation, which is reflected in the monitor station ranging measurements. The carrier, on the other hand, experiences a "phase advance," which affects measurements made in a carrier frequency tracking (phase lock) loop. By taking the difference between the ranging measurements and the integrated Doppler effect on the carrier, the change in the ionospheric delay is obtained. This paper presents the results of both methods and discusses their consistency and quality.

Typical results are shown in Figs. 2-1 through 2-4. During a 90-min interval (9 October 1978), continuous tracking data was acquired at the Guam monitor station, from 13:50 to 15:20 Pacific Daylight Time (PDT). At about the same time, there was an 80-min period when data was acquired at the Vandenberg monitor station, from 14:33 to 15:53 PDT. Figure 2-1 shows the ionospheric delay at the Guam monitor station as obtained by using the difference in range as measured from the two carrier frequencies. Figure 2-2 shows the same ionospheric delay as measured by taking the time difference between ranging measurements and the integrated Doppler as measured at the carrier frequency; only the L_1 carrier was used for these

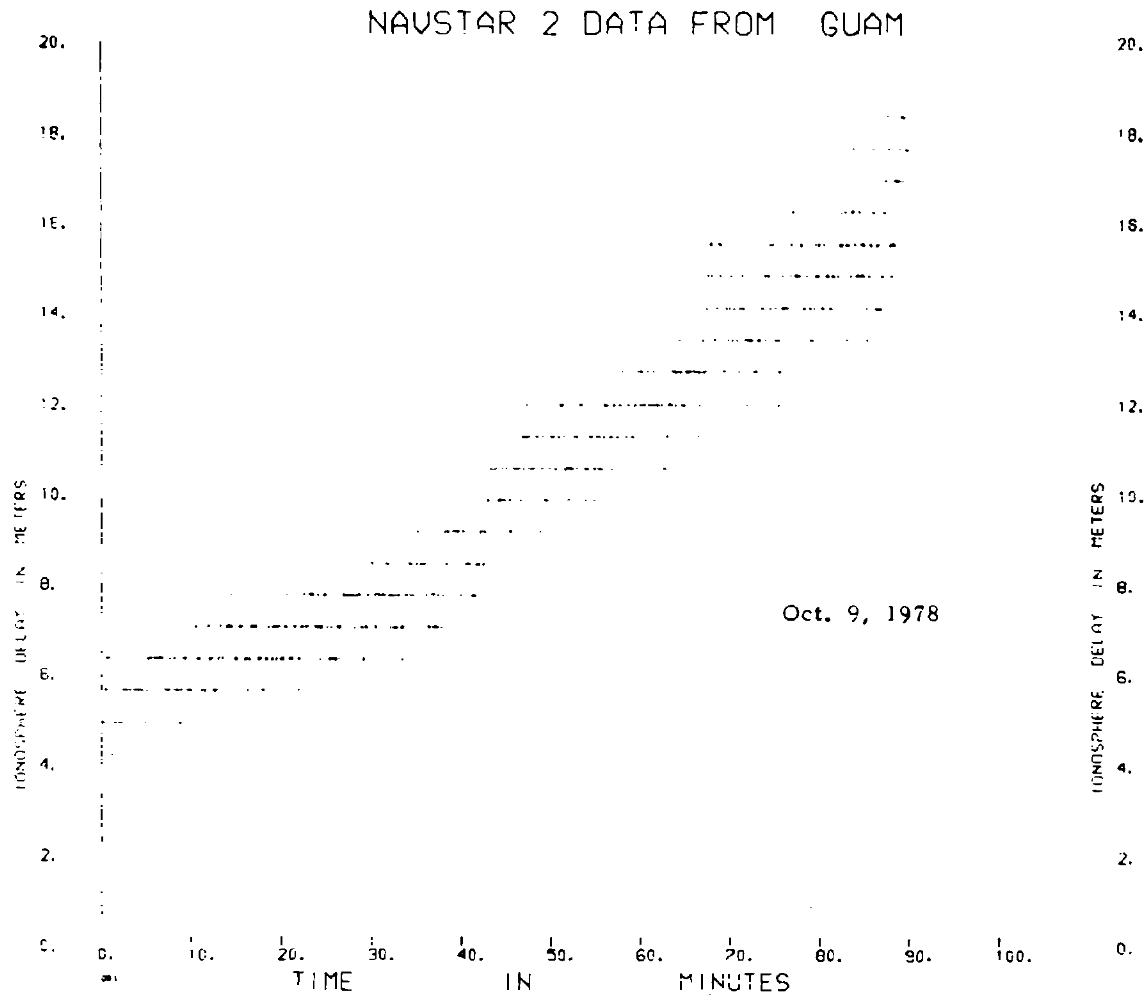


Fig. 2-1. Navstar 2 Data from Guam: Two Frequency Method

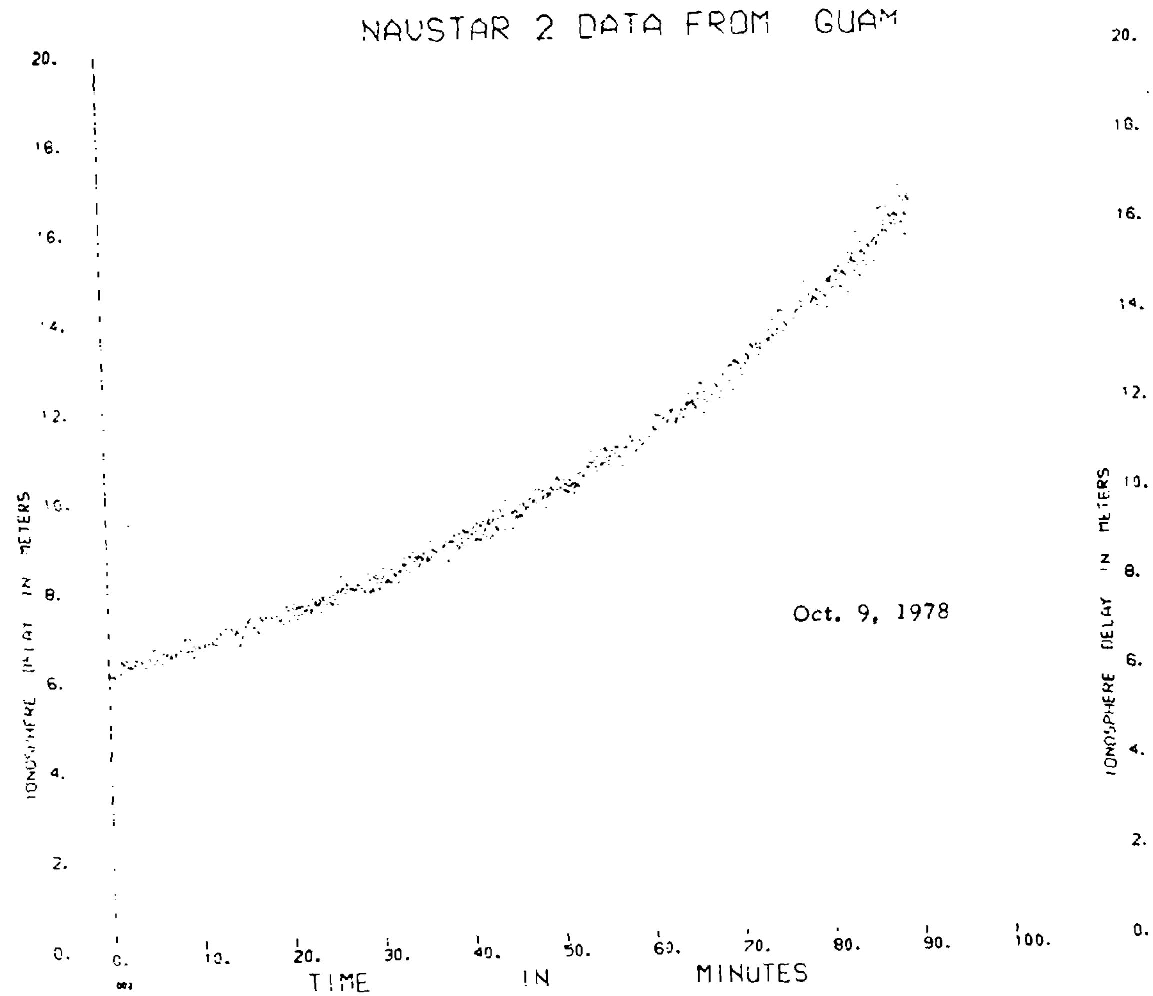


Fig. 2-2. Navstar 2 Data from Guam: Group Delay Minus Phase Advance Method

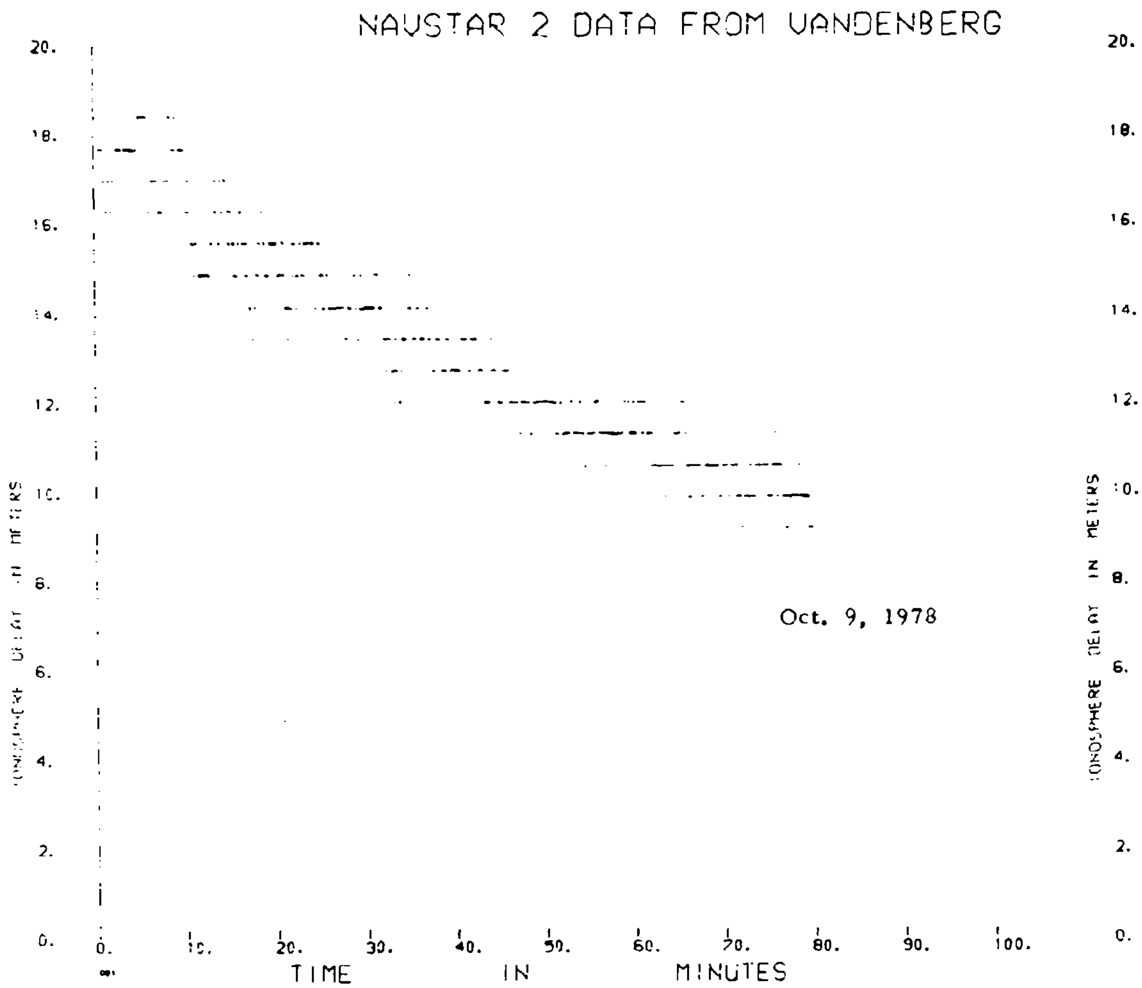


Fig. 2-3. Navstar 2 Data from Vandenberg: Two Frequency Method

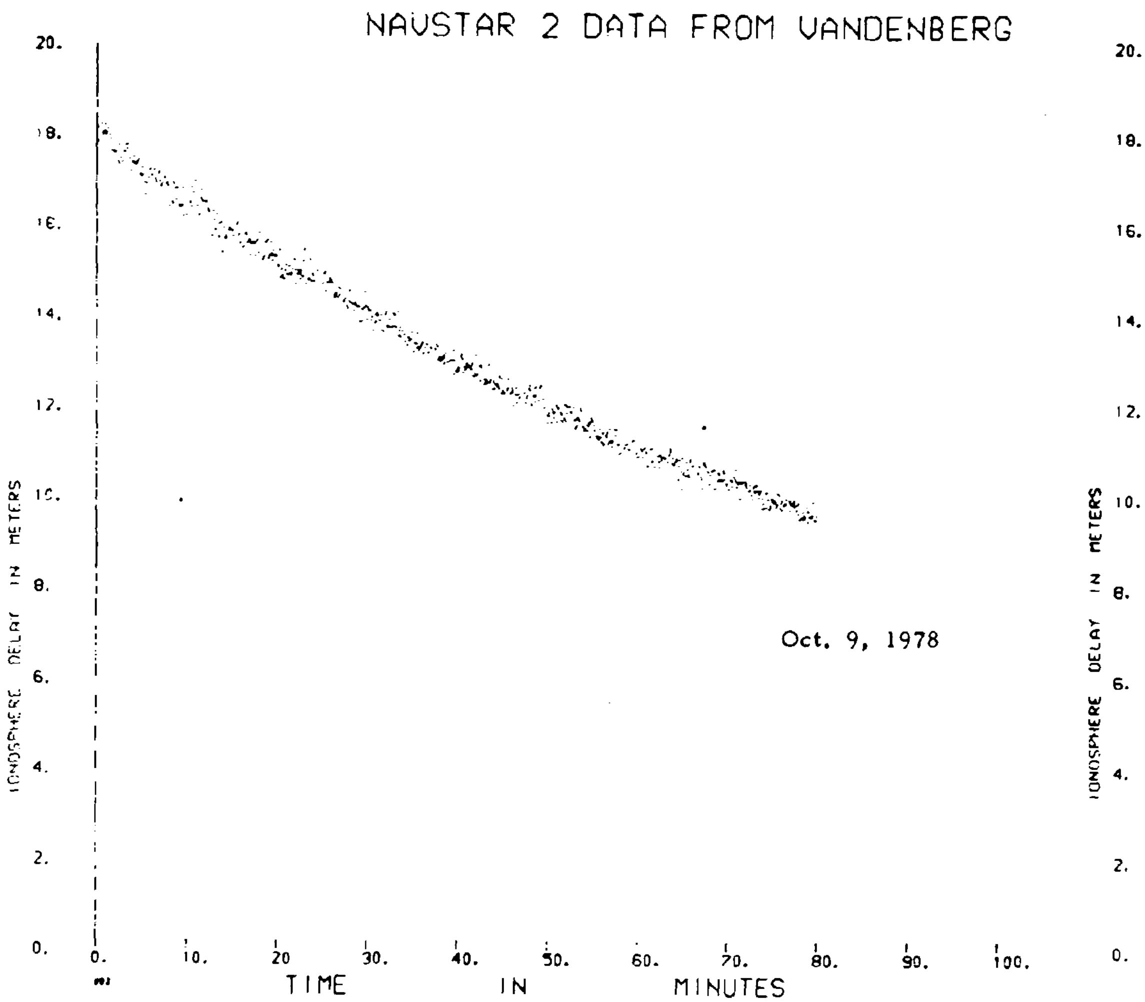


Fig. 2-4. Navstar 2 Data from Vandenberg: Group Delay Minus Phase Advance Method

ranging and Doppler measurements (by this method only the change in the ionospheric delay is obtained). The absolute level shown in Fig. 2-2 has been selected to match the average delay from the two frequency method. The consistency in the shape of these two plots lends credence to both techniques for performing ionospheric measurements. As shown in the plots, this was for a time of day when the ionospheric effect was increasing at Guam. Adding to this effect is the fact that the satellite elevation angle was decreasing relative to Guam. The reverse is the case for the data taken at Vandenberg (Figs. 2-3 and 2-4); the satellite elevation angle was increasing, and the ionospheric effect decreases during these afternoon hours. Here again, there is good agreement between the two types of ionospheric measurements.

III. OVERVIEW OF NAVSTAR PHASE I ORBIT CONFIGURATION

The baseline orbit configuration for Navstar Phase I is shown in Table 3-1. Navstar satellites 1, 2, and 3 are currently on-orbit. Navstar 1 occupies position 1, Navstar 2 position 5, and Navstar 3 position 6. For convenience, this data is referenced to the beginning of the day, midnight (0 hr) Greenwich Mean Time (GMT) on 1 January 1979. On this particular date the reference ground trace of satellite 1 will first cross the equator (north to south) at a longitude of 47.0 deg at 4:44.5 GMT. Approximately 11 hr and 58 min later it will again cross the equator (south to north), this time at a longitude of 227.0 deg. The time of the ascending node crossings will differ for other days during the year.

The ground trace of the satellite orbits is fixed from day to day and therefore repeats itself every 23 hr, 55 min, and 56.6 sec. Most of the deviation from a 24-hr period is due to the difference between a solar and a sidereal day, but a small part is due to the rotation of the orbit planes due to the earth's oblateness and to sun and moon effects. This longitudinal motion, or precession, is slightly different for each orbit but averages about 11.5 deg per year. The satellites thus appear 4 min and 3.4 sec earlier each day.

The information in Table 3-1 can be used to compute the times of visibility of the satellites for any location on earth as of 1 January 1979. For other days during 1979, the times are advanced 4 min and 3.4 sec for each day after 1 January.

Table 3-1. Navstar Phase I Orbits at First Ascending Node on 1 January 1979

Satellite Position No.	Nodal Period, sec	Inclination, deg	Nominal Longitude of First Ascending Node, deg	Right Ascension of the Ascending Node[a], deg	Nominal Time of First Ascending Node (GMT)	Eccentricity e	Argument of Perigee, deg
1	43,078.3	63.25[b]	47.0	217.98	$4^h\ 44^m\ 30^s$	0.0038	343
2	43,078.3	63	68.5	219.49	$3^h\ 24^m\ 45^s$	0	0
3	43,078.3	63	89.5	219.49	$2^h\ 00^m\ 54^s$	0	0
4	43,078.3	63	310.5	99.48	$3^h\ 16^m\ 16^s$	0	0
5	43,078.3	63.18[b]	332.0	100.27	$1^h\ 54^m\ 7^s$	0.0048	97
6	43,078.3	63[b]	353.0	99.49	$0^h\ 27^m\ 15^s$	0	0

[a]Referenced to astronomical of 1950.0.

[b]Actual values of orbit. Values for other satellite orbits are nominal.

IV. SIGNAL STRUCTURE

Each satellite transmits a navigation signal on two L-band frequencies, one at 1575.42 MHz (L_1) and the other at 1227.6 MHz (L_2). These two carrier frequencies are biphase modulated by pseudo random sequences providing a spread spectrum modulation. The L_1 carrier is actually modulated by two such sequences in phase quadrature so that, strictly speaking, this carrier is actually quadraphase modulated. One pseudo random sequence is a precision (P) signal at a random pulse repetition rate of 10.23 MHz and is an extremely long code so that for all practical purposes it is a truly random sequence. The second pseudo random sequence is a coarse acquisition (C/A) signal, which is a short sequence used either for initial acquisition of the P signal or as a less accurate navigation signal for low-cost users. The L_2 carrier frequency is biphase modulated only by the P signal or, as a ground-controlled option, only by the C/A signal.

The pseudo random sequence is generated by a feedback shift register, the output of which modulates the carrier (Fig. 4-1). The P signal pseudo random sequence generator is functionally illustrated in Fig. 4-2. By combining four 12-stage feedback shift registers, the equivalent of a 48-stage shift register is obtained. Using a pseudo random sequence to biphase modulate the carrier results in the transmitted spectrum being spread as illustrated in Fig. 4-3. This spread prevents an interference signal from being rejected in the receiver in the following manner: The receiver's pseudo random sequence generator modulates the incoming signal in the same manner as the generator on the satellite (the two generators are the same). The original carrier frequency is thus reconstructed and is collapsed to a very narrow band. The interference signal, however, is spread out over a wide spectrum, and this signal can therefore be filtered out so that only a small residue remains near the now-reconstructed carrier frequency.

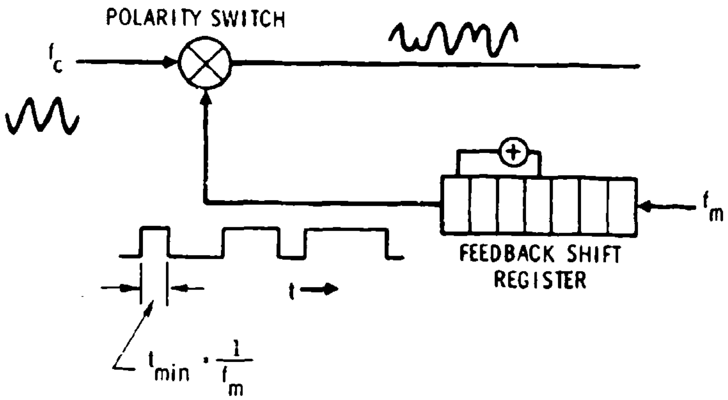
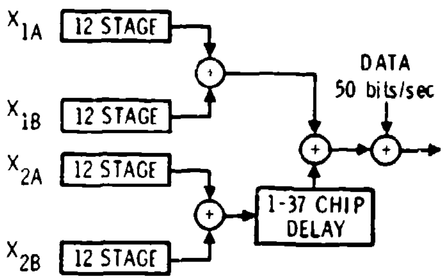


Fig. 4-1. Pseudo Random (Noise) Code



CHARACTERISTICS	CODE PROPERTIES
RATE	10.23×10^6 bits/sec
PERIOD	$\approx 2^{48} - 1$ 267 days
TYPE CODE	LINEAR, NON-MAX LENGTH
CORRELATION PROPERTIES	~ 36 dB

Fig. 4-2. Code Generator

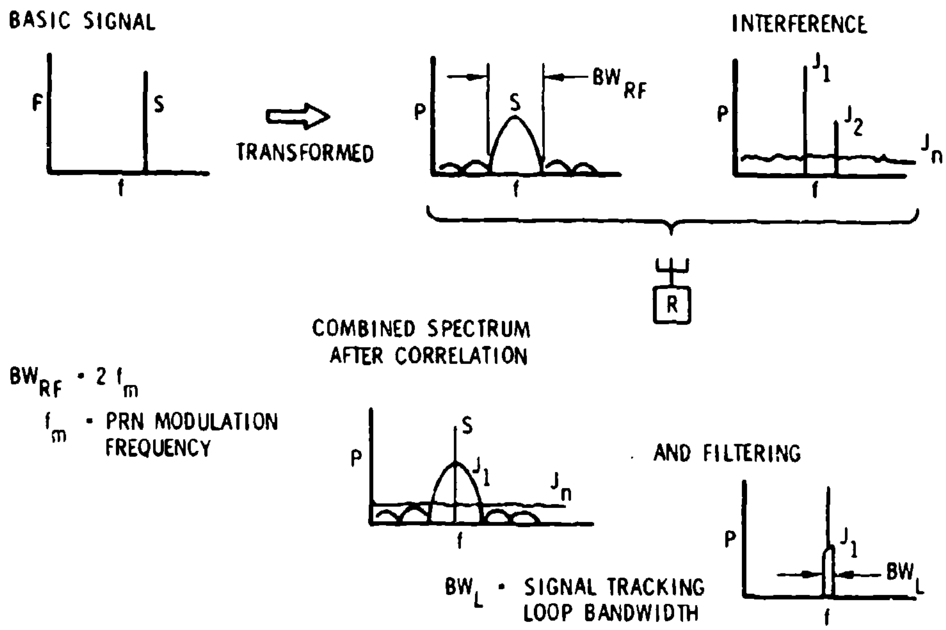


Fig. 4-3. Pseudo Random Noise-Spread Spectrum

V. GENERIC RECEIVER

Functionally, Navstar receivers used at the monitor stations incorporate two tracking loops, which must operate simultaneously to properly track the Navstar navigational signal. The first is the code tracking loop, which tracks the pseudo random sequence by matching the locally generated sequence with the sequence on the received signal. Simultaneously, a phase lock loop is tracking the carrier frequency. The actual process is much more complicated because of the necessary intermediate frequency (IF) downconversion steps. For simplicity, however, these downconversion steps are omitted in the functional diagram shown in Fig. 5-1. Figure 5-2 expands on the function of such a receiver by illustrating the role of a feedback shitt register and envelope detectors in the code lock loop that tracks the incoming pseudo random sequence. There are three ouputs of the feedback shift register: an on-time sequence P_O, an early sequence P_E, and a late sequence P_L. The early and late codes modulate the carrier frequency C, which is synthesized in the phase lock loop. These signals are then mixed with the incoming signal, thereby generating voltages proportional to the extent that the sequences match the incoming sequence from the satellite. The difference between these two signals generates an error voltage that drives a voltage control oscillator (VCO) with which the feedback shift register is synchronized, thereby tracking the incoming random sequence (Fig. 5-3).

The on-time pseudo random sequence is mixed with the incoming signal to reconstruct the carrier signal. The phase lock loop (which is actually a bistable Costas loop) tracks this satellite-transmitted carrier. Binary data is added modulo-2 to the P signal pseudo random sequence at a rate of 50 bps. Since only the pseudo random sequence is removed from the incoming signal, the 50-bps data sequence still remains on the signal, but the single-sided bandwidth of this signal is now only about 50 Hz. In addition to maintaining phase lock on the carrier signal, the Costas loop strips off the data remaining on the signal (Fig. 5-4).

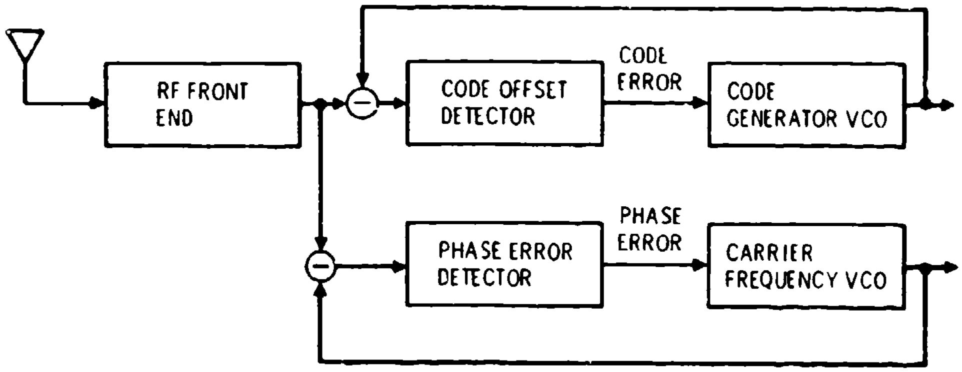


Fig. 5-1. Simplified Diagram of Generic Receiver

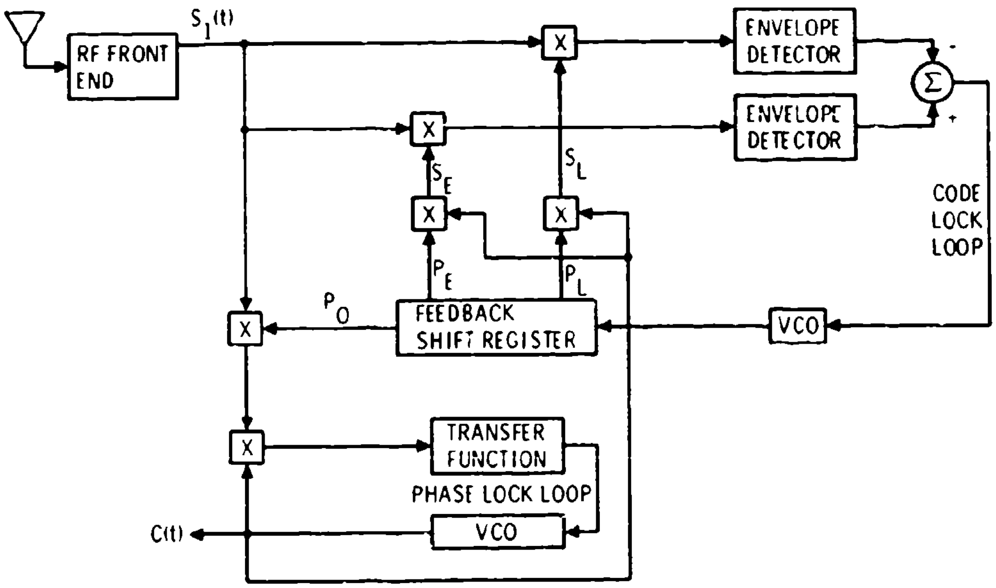


Fig. 5-2. Generic Pseudo Random Noise Receiver Functional Block Diagram

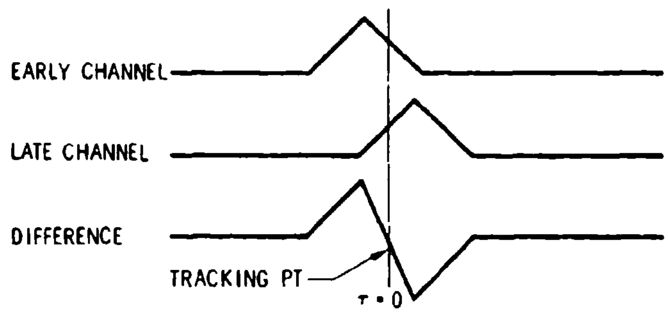


Fig. 5-3. Correlation Principle

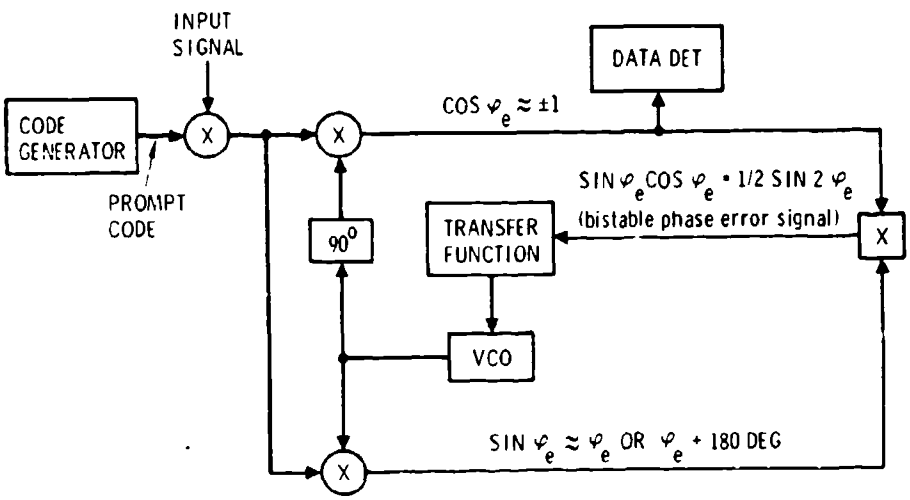


Fig. 5-4. Costas (Phase Lock) Loop

VI. NAVSTAR MONITOR STATIONS

Each monitor station has a receiver that tracks both the pseudo random sequence and the carrier signal. Tracking the incoming pseudo random sequence allows the receiver to make a range measurement to the satellite. If the atomic frequency standard at the monitor station were synchronized exactly with the standard in the satellite, this measurement would be a true measure of the distance from the monitor station to the satellite. In a practical situation, however, there is always some bias between the monitor stations and the satellite atomic frequency standards, and because of this relative clock difference the range measurement is referred to as pseudo range. This bias is determined as part of the ephemeris and clock parameter estimation process in the MCS computer, and since it is known to some degree of accuracy, the pseudo range measurements can be considered a measure of the absolute distance from the monitor station to the satellite.

Tracking the carrier signal, however, does not provide absolute ranging measurements; only changes in the range can be measured from carrier tracking. At the Navstar monitor stations, the changes in range are measured in the phase lock loop over successive 6-sec intervals. These range changes are referred to as delta range measurements.

An important device used in both the code and carrier tracking loops is an incremental phase modulator (IPM), a digital frequency synthesizer that is in effect the actual VCO. The IPM performs relative to the frequency standard in the monitor station. The quantization of each step is 1/64 of the wavelength of the quantity being tracked. Since the chipping rate of the pseudo random sequence corresponds to about 30 m, the quantization of the code tracking loop is about 0.46 m. Similarly, since the wavelength of the carrier frequency is about 19 cm, the quantization in the phase lock loop is about 0.3 cm. Because of this two-order-of-magnitude difference in

quantization between the code and carrier tracking loops, the tracking accuracy of the phase lock loop is much greater than that of the code loop.

VII. DISCUSSION OF IONOSPHERIC DELAY

Because of the ionosphere, the Navstar navigation signal experiences an excess delay over the free space propagation time between the satellite and the monitor stations. This time delay is proportional to the number of free electrons encountered along the signal path. The integrated number of electrons encountered per unit area is commonly referred to as the total electron content. For frequencies above 200 MHz, the delay is essentially inversely proportional to the square of the frequency. This frequency dependence is the basis for using two frequency measurements to calibrate the ionospheric delay.

The dominant factors that determine the total electron content are the earth location at which the observation is made, the time of day, the season of the year, and the time during the eleven-year solar sunspot cycle. In addition, the direction of the line of sight from the ground observer to the Navstar satellite (azimuth and elevation angles) has an important bearing on the total electron content.

Several types of ionospheric variations may occur: severe disturbances, traveling disturbances, and scintillations. Severe disturbances are due to magnetic storms and occur only a very small percentage of the time; their occurrence is often predictable hours to days in advance. Traveling disturbances are low-magnitude, low-frequency, isolated disturbances that also occur infrequently. Scintillations are high-frequency, noise-like amplitude and phase fluctuations on received signals arising from irregularities in the electron density distributions of the ionosphere.

Thus, the ionospheric delay is determined by a composite of many parameters. While the basic function of Navstar is worldwide accurate navigation, a potentially important by-product is the capability of the Navstar satellites to provide enormous quantities of high-quality data

concerning the ionosphere, which should have great scientific value and lead to a more accurate model of the ionosphere. This would be especially beneficial to the low-cost Navstar user.

The use of two frequencies for measuring the ionosphere will now be considered. By taking advantage of the inverse square relationship between the delay and the frequency of transmission, the delay at the L_1 and L_2 frequencies can be expressed by

$$D1 = \frac{K}{f_1^2} \qquad D2 = \frac{K}{f_2^2} \tag{7-1}$$

where D1 and D2 are the delays in meters at the L_1 and L_2 frequencies respectively, and K is a proportionality constant relating ionospheric delay to frequency. The quantity measured at the monitor stations is the difference in the delays given by the above relationships. This difference is given by

$$D = D2 - D1 = K\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right) \tag{7-2}$$

The constant of proportionality K is therefore given by

$$K = \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} D \tag{7-3}$$

Substituting Eq. (7-3) into Eq. (7-1), the ionospheric delay at each of the two frequencies is related to the differential delay measured at the monitor station and is given by

$$D1 = \frac{f_2^2}{f_1^2 - f_2^2} D \qquad D2 = \frac{f_1^2}{f_1^2 - f_2^2} D \tag{7-4}$$

Substituting the actual values of the two frequencies yields

$$D1 = 1.54573D \qquad D2 = 2.54573D \tag{7-5}$$

As a consequence of the inverse square relationship, there is a "group delay" of the pseudo random noise biphase modulation of the L-band carrier (the PRN sequence at 10.23 MHz). At the same time, there is a "phase advance" of the carrier wave itself (1575.42 and 1227.6 MHz). What this means is that while the actual propagation is delayed by the ionosphere, a phase shift of the carrier will occur which can make it appear that the velocity of propagation of the carrier is actually increasing relative to the velocity of free space propagation, i.e., it appears to go faster than the velocity of light. How this interesting phenomenon comes about will now be explored.

For the purpose of this demonstration, consider the simple case of a carrier frequency being modulated by a single frequency modulation. There is no loss of generality in using such a simplified model because PRN biphase modulation is really a situation in which the carrier frequency is modulated by a continuous spectrum of sine waves. Therefore, a demonstration of the effect of one of these sine waves is equivalent to a demonstration of the full spectrum of sinusoidal modulation. The voltage received at the monitor station antenna can thus be expressed by

$$v = V \sin(2\pi f_m t)\sin(2\pi f_c t) \tag{7-6}$$

where

v = instantaneous voltage

V = voltage amplitude

f_m = modulating frequency

f_c = carrier frequency

t = time

Further, let $\omega_m = 2\pi f_m$ and $\omega_c = 2\pi f_c$. This modulated carrier breaks down as

$$v = \frac{1}{2} V \cos[(\omega_c - \omega_m)t] - \frac{1}{2} V \cos[(\omega_c + \omega_m)t] \tag{7-7}$$

The actual voltage received at the antenna consists of two distinct frequencies: one is the carrier plus the modulating frequency, and the other is the carrier minus the modulating frequency. Now consider a time delay due to the ionosphere at each of these two frequencies so that the delayed voltage will be given by

$$v = \frac{1}{2} V \cos[(\omega_c - \omega_m)(t + t_L)] - \frac{1}{2} V \cos[(\omega_c + \omega_m)(t + t_H)] \tag{7-8}$$

where t_L and t_H are the time delays at the lower and higher frequencies respectively. These two time delays are proportional to the inverse square of the difference and sum frequencies respectively, and may therefore be expressed by

$$t_L = \frac{K}{(\omega_c - \omega_m)^2} \qquad t_H = \frac{K}{(\omega_c + \omega_m)^2} \tag{7-9}$$

where K is again a proportionality constant relating ionospheric delay to frequency. Substituting these equations into Eq. (7-8), the following relationship is obtained for the delayed voltage at the receiver antenna

$$v = \frac{1}{2} V \cos\left[(\omega_c - \omega_m)\left(t + \frac{K}{(\omega_c - \omega_m)^2}\right)\right] - \frac{1}{2} V \cos\left[(\omega_c + \omega_m)\left(t + \frac{K}{(\omega_c + \omega_m)^2}\right)\right] \qquad (7\text{-}10)$$

Upon recombining the terms in Eq. (7-10), the following expression for this voltage is obtained

$$v = V \sin\left[\omega_m\left(t - \frac{K}{\omega_c^2 - \omega_m^2}\right)\right] \times \sin\left[\omega_c\left(t + \frac{K}{\omega_c^2 - \omega_m^2}\right)\right] \qquad (7\text{-}11)$$

Since $\omega_c^2 \gg \omega_m^2$, Eq. (7-11) can be written as

$$v = V \sin\left[\omega_m\left(t - \frac{K}{\omega_c^2}\right)\right] \sin\left[\omega_c\left(t + \frac{K}{\omega_c^2}\right)\right] \qquad (7\text{-}12)$$

The voltage is now (as originally) a carrier frequency f_c, which is modulated sinusoidally at the modulation frequency f_m. Because of the ionospheric delay, the phase of the modulation is delayed by an amount K/ω_c^2, whereas the phase of the carrier frequency is advanced by an equal amount. The Navstar monitor stations operate such that they can distinguish between the modulating and the carrier frequencies. The PRN code tracking loop does indeed operate on the modulating frequency, and the pseudo range

measurements will directly reflect the delay in modulation due to the ionosphere. On the other hand, the carrier frequency phase lock loop, which measures change in range by tracking the carrier, will experience an advance due to the phase advance indicated in Eq. (7-12). This difference between code and carrier tracking can be directly utilized to measure the change in ionospheric delay.

The procedure for measuring this change in ionospheric delay is as follows. The difference in pseudo range is computed at the beginning and the end of a time interval. The integrated Doppler, or delta range, is measured in the phase lock loop over the same time interval and is subtracted from the pseudo range difference. Because the ionosphere has opposite effects on the phases of the code and the carrier, this result will equal twice the ionospheric delay. Therefore, the change in ionsopheric delay is given by

$$D = \frac{1}{2}\left[PR_{t2} - PR_{t1} - \int_{t1}^{t2} (DR)dt\right] \tag{7-13}$$

where

D = ionospheric delay

PR_{t1}, PR_{t2} = pseudo range measurements at the beginning and end of the time interval

DR = range rate

To summarize, two techniques are available to measure the ionospheric delay with the Navstar navigation signal. The first method, using two carrier frequencies, provides an absolute measurement of the delay. The second method (which, it should be noted, uses only one carrier frequency) does not provide the total delay, it only provides a measure of the change in the ionospheric delay over a period of time. But, as will be shown, this second method is inherently much more accurate. Consequently, the two methods actually complement each other and make it possible to measure the ionosphere with great accuracy.

VIII. ACCURACY CONSIDERATIONS

The equation for obtaining the ionospheric delay based on the difference of pseudo range measurements at two frequencies for the L_1 frequency (from Sec. VII) is given by

$$D1 = 1.54573 \times D = 1.54573(PR_{L2} - PR_{L1}) \qquad (7-5)$$

where PR_{L1} and PR_{L2} are the pseudo range measurements at the L_1 and L_2 frequencies respectively.

Consider now the effect of random errors in the pseudo range measurements at both the L_1 and L_2 frequencies on obtaining the delay at the L_1 frequency. Assuming, for the moment, that these two error sources are random and uncorrelated, the error in determination of the ionospheric delay at the L_1 frequency is given by

$$\sigma_{D1}^2 \doteq 2.39(\sigma_{L1}^2 + \sigma_{L2}^2) \qquad (8-1)$$

where σ_{D1} is the one-sigma error in obtaining the ionospheric delay at the L_1 frequency and σ_{L1} and σ_{L2} are the one-sigma errors in the pseudo range measurements at the L_1 and L_2 frequencies respectively.

Similarly, the expression for the random error in determining the ionospheric delay at the L_2 frequency is given by

$$\sigma_{D2}^2 = 6.48(\sigma_{L1}^2 + \sigma_{L2}^2) \qquad (8-2)$$

The expression for the ionospheric delay based on the group delay/ phase advance phenomenon (see Sec. VII) is given by

$$D = \frac{1}{2}\left[PR_{t2} - PR_{t1} - \int_{t1}^{t2} (DR)dt\right] \tag{7-13}$$

The random error in determining the change in ionospheric delay is given by

$$\sigma_D^2 = 0.25\left(\sigma_{t2}^2 + \sigma_{t1}^2 + \text{Doppler error}^2\right) \tag{8-3}$$

where σ_D is the one-sigma error in obtaining the change in ionospheric delay and σ_{t1} and σ_{t2} are the one-sigma errors in the pseudo range measurements at beginning and end of the time interval over which this delay is being measured.

As discussed in Sec. VI, the random error in PRN code tracking is much greater than the random error in phase lock loop tracking of the carrier frequency. Consequently, for all practical purposes the only error in determining the change in ionospheric delay is that due to the measurements of pseudo ranges at the beginning and end of the time interval. The error may thus be expressed as

$$\sigma_D^2 = 0.25\left(\sigma_{t2}^2 + \sigma_{t1}^2\right) \tag{8-4}$$

A comparison of Eq. (8-4) with Eqs. (8-1) and (8-2) shows that the expected random error in the measurements based on the group delay/phase advance is only about 20 and 32 percent of the random error that can be expected from ionospheric delay measurements using the two frequency technique. On the other hand, the two frequency technique provides an absolute measurement of the ionospheric delay, whereas the other method provides only time changes in the delay. By performing both types of measurements, it is possible to enjoy the best of both worlds.

For fine detail, the group delay/phase advance method is used; the average delay over the interval for which these measurements are made is obtained by taking the average measurement from the two frequency method obtained over the same time interval. In this way the results from the two frequency method can be made much more accurate because of the added advantage of being able to average all data taken in a pass. The random error inherent in making pseudo random measurements can in large measure be averaged out. The application of this concept of merging the two types of ionospheric delay measurements is illustrated in several examples presented in the next section.

IX. EXAMPLES OF IONOSPHERIC MEASUREMENTS

Figures 9-1 through 9-12 illustrate the ionospheric measurements obtained from three satellites at two monitor stations. Both the group delay minus phase advance and the two frequency method for obtaining ionospheric delay are presented. On 15 November 1978, the Vandenberg monitor station continuously tracked Navstars 1, 2, and 3 over a 2-1/2-hr time span, from 12:10 to 14:40 Pacific Standard Time (PST). During a one-hr period within this time span the Alaska monitor station also simultaneously tracked the three Navstar satellites.

Figures 9-1 and 9-2 show the results from Tracking Navstar 1 at Vandenberg, Figs. 9-3 and 9-4 from Navstar 2, and Figs. 9-5 and 9-6 from Navstar 3. Figures 9-7 and 9-8 show the results from Navstar 1 at Alaska, Figs. 9-9 and 9-10 from Navstar 2, and Figs. 9-11 and 9-12 from Navstar 3.

During the 2-1/2-hr interval, Navstars 1 and 2 were both at a high elevation angle relative to the Vandenberg monitor station. Consequently, the pattern of the ionospheric delay as measured from these two satellites is similar, and the magnitude is low (two to four meters). Navstar 3 is ahead of Navstar 2 in the same orbit plane and was going to a lower elevation angle relative to Vandenberg during this period. Consequently, the ionospheric delay was significantly increasing.

During the one hour when the satellites were being tracked at the Alaska monitor station, Navstar 1, which is in a different orbit plane from Navstars 2 and 3, was moving northeast, whereas Navstars 2 and 3 were moving southeast. Therefore, the trend was for the delay from Navstar 1 to decrease, but the trend for Navstar 2 was the reverse. Note again that Navstar 3 is ahead of Navstar 2 (it was going to a lower elevation angle relative to Alaska), and thus the ionospheric delay from Navstar 3 was rapidly increasing.

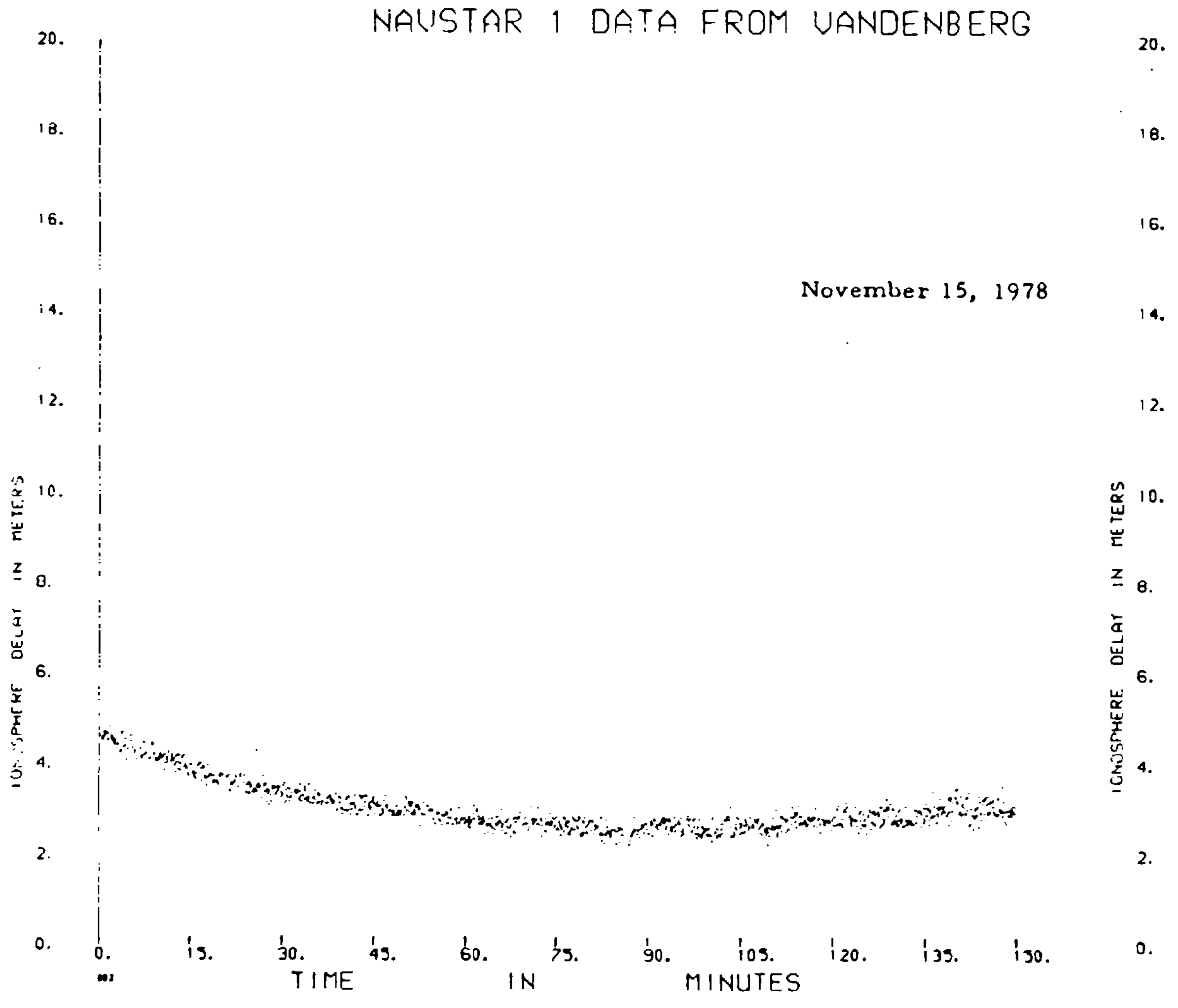


Fig. 9-1. Navstar 1 Data from Vandenberg: Group Delay Minus Phase Advance Method

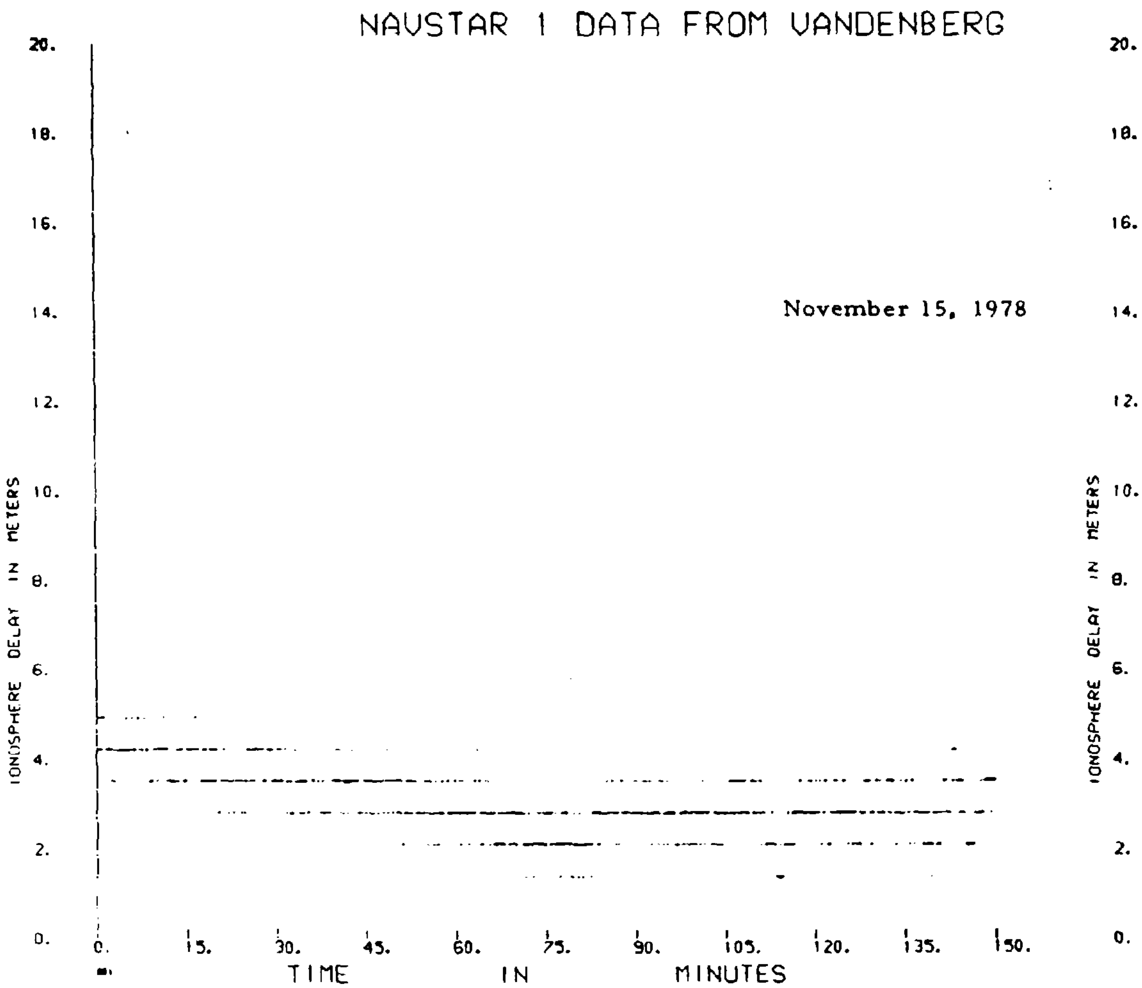


Fig. 9-2. Navstar 1 Data from Vandenberg: Two Frequency Method

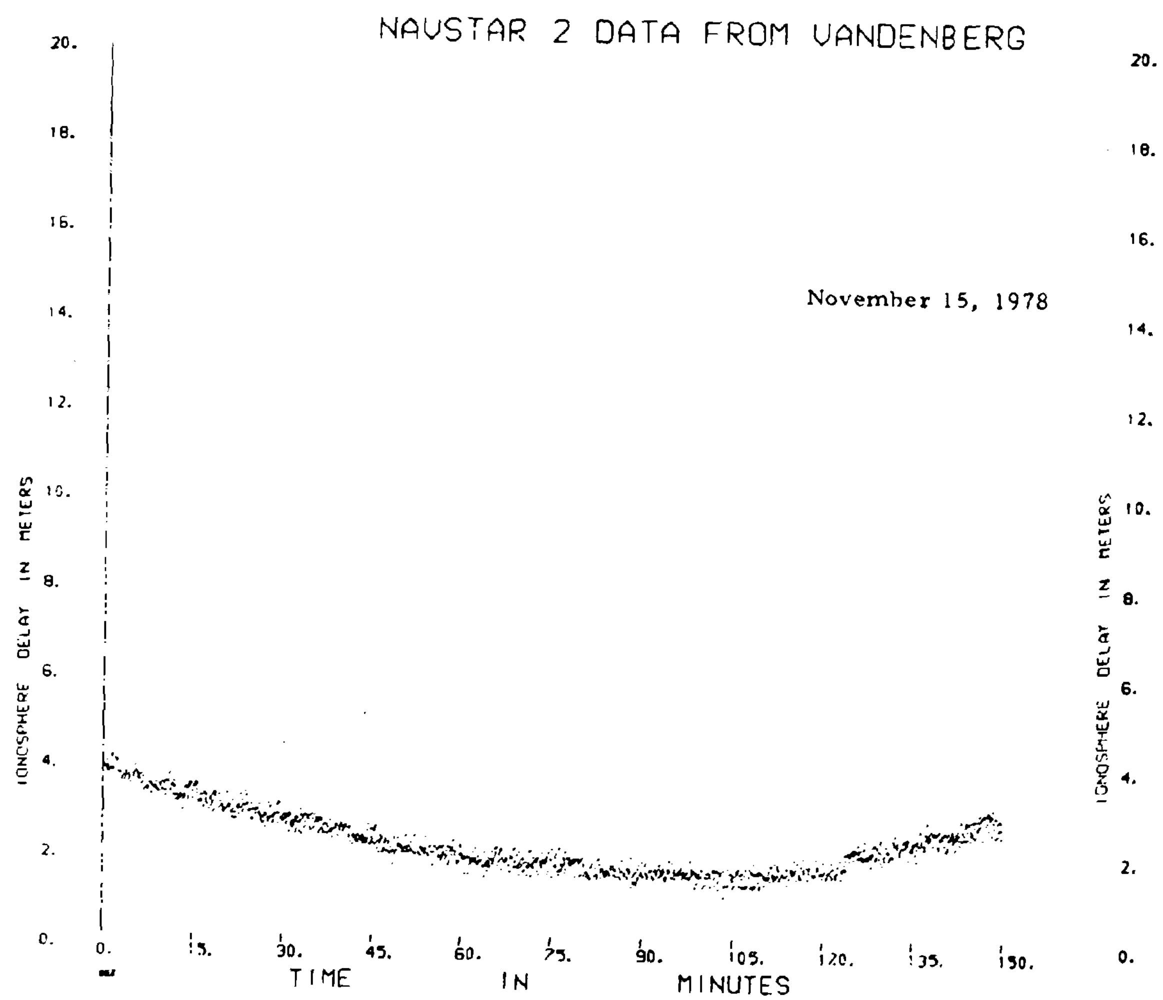


Fig. 9-3. Navstar 2 Data from Vandenberg: Group Delay Minus Phase Advance Method

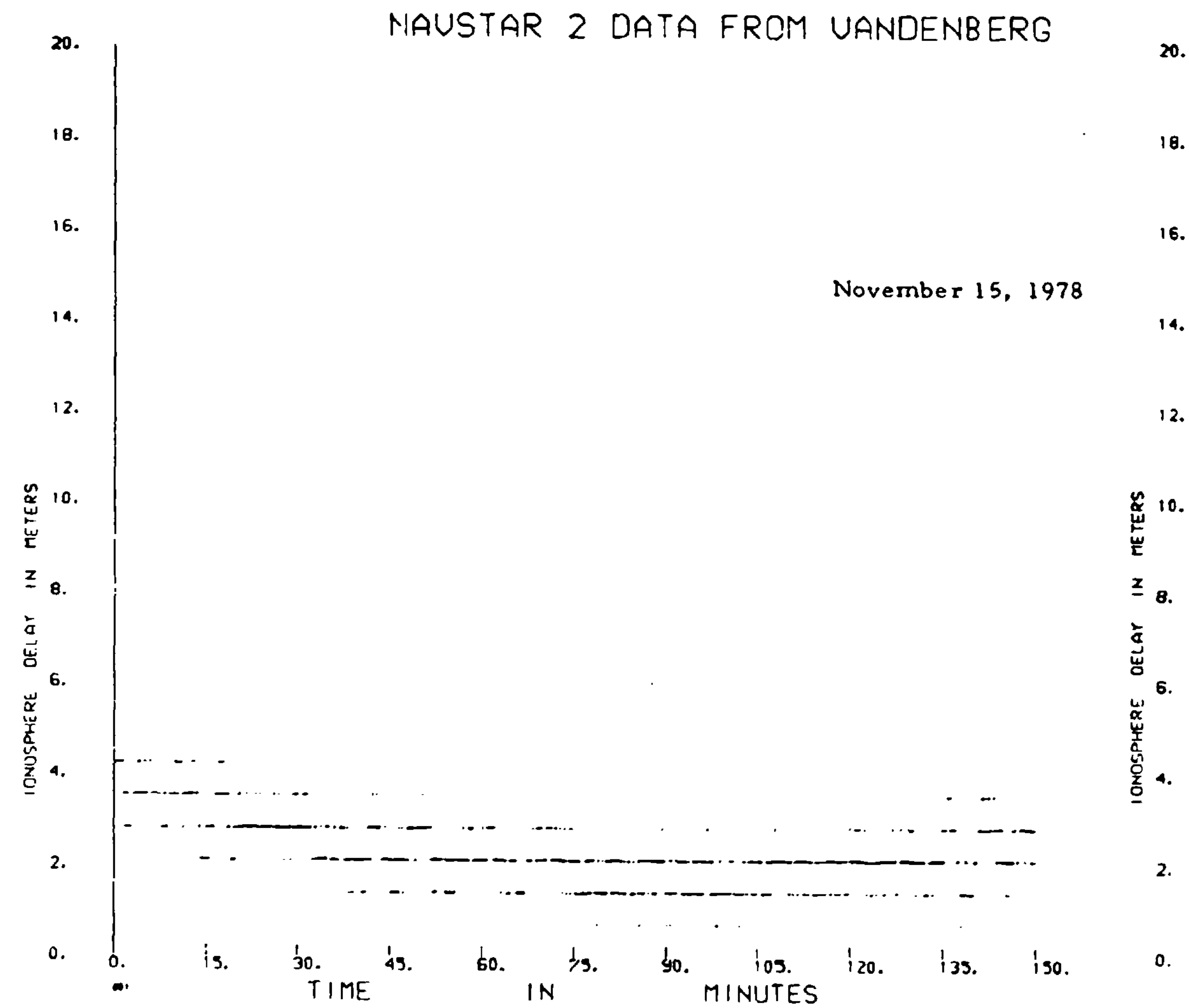


Fig. 9-4. Navstar 2 Data from Vandenberg: Two Frequency Method

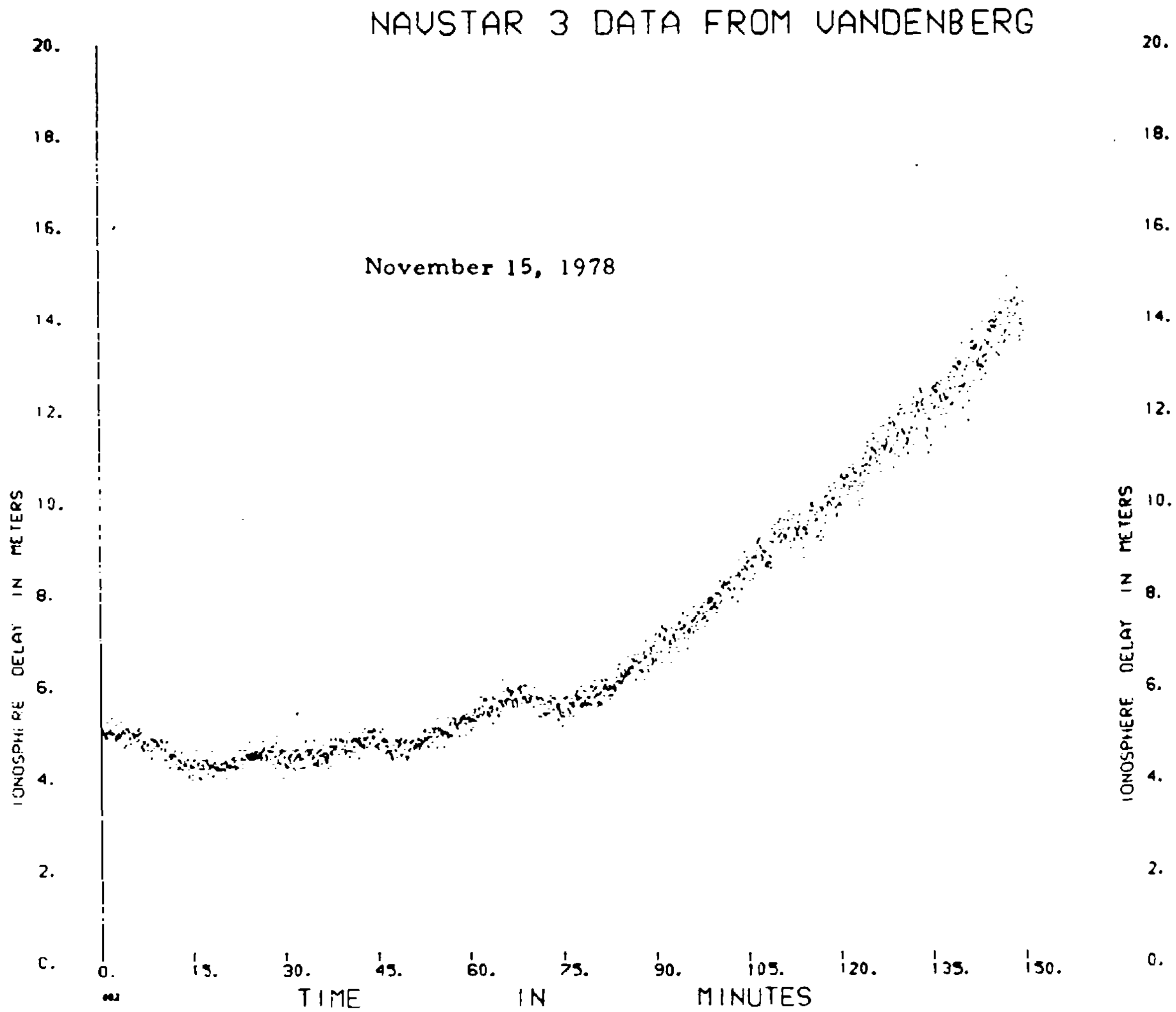


Fig. 9-5. Navstar 3 Data from Vandenberg: Group Delay Minus Phase Advance Method

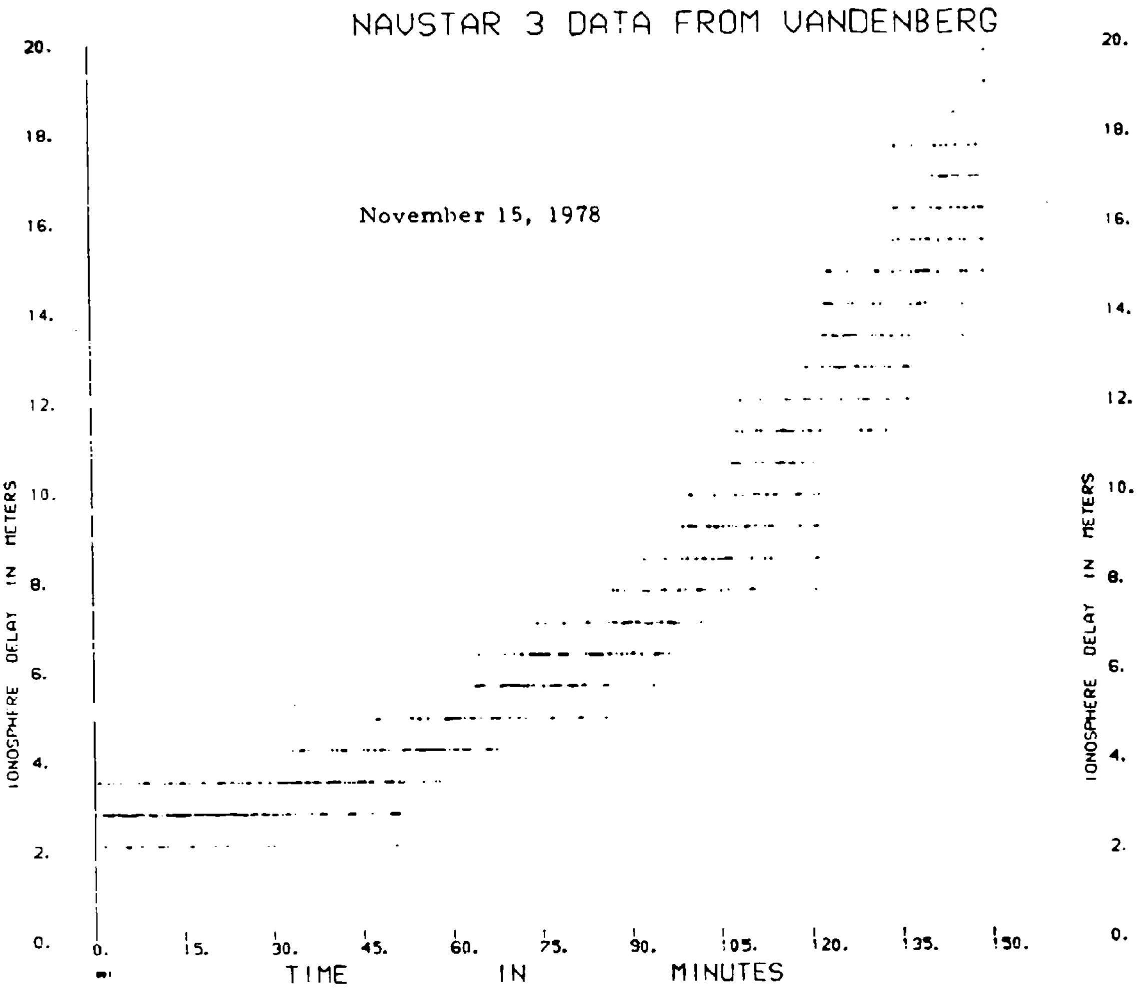


Fig. 9-6. Navstar 3 Data from Vandenberg: Two Frequency Method

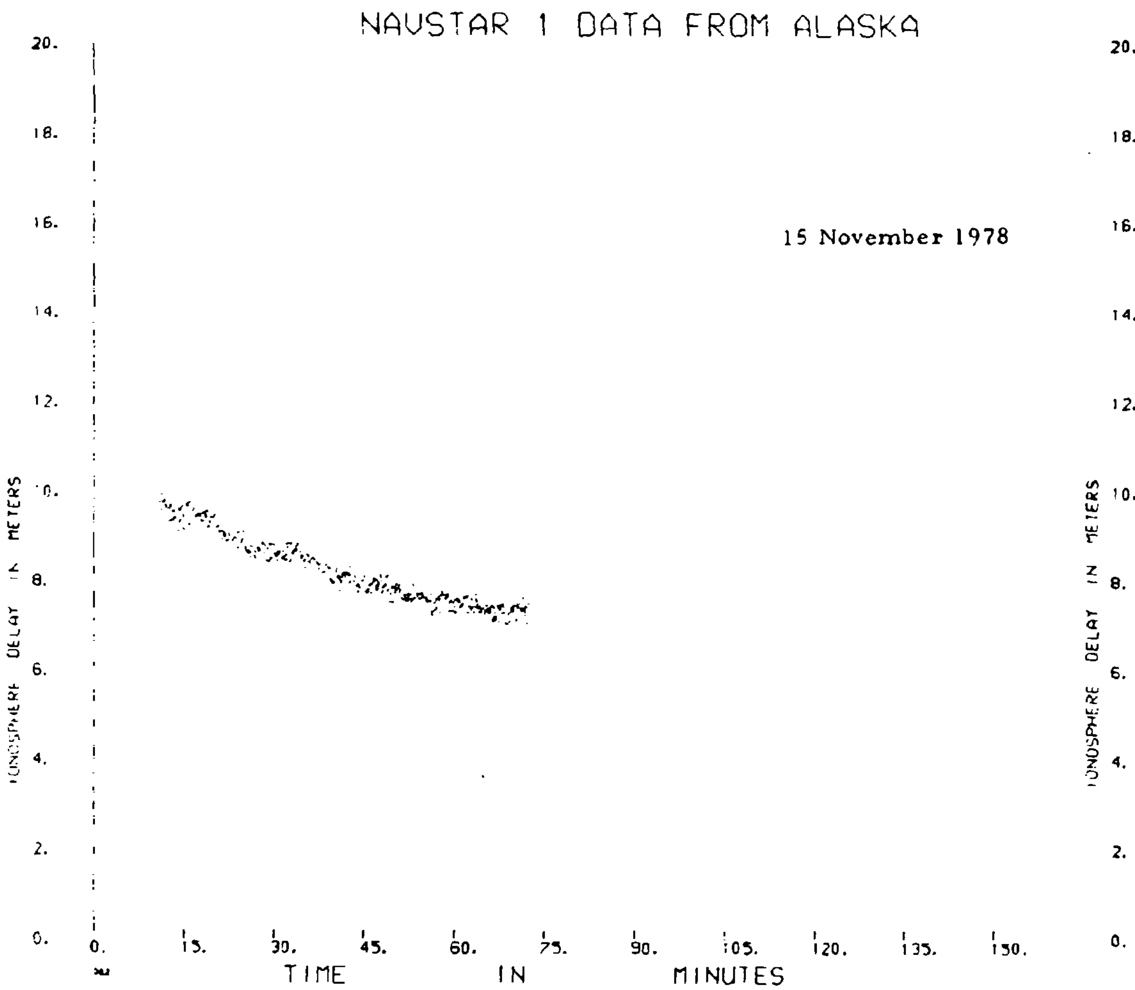


Fig. 9-7. Navstar 1 Data from Alaska: Group Delay Minus Phase Advance Method

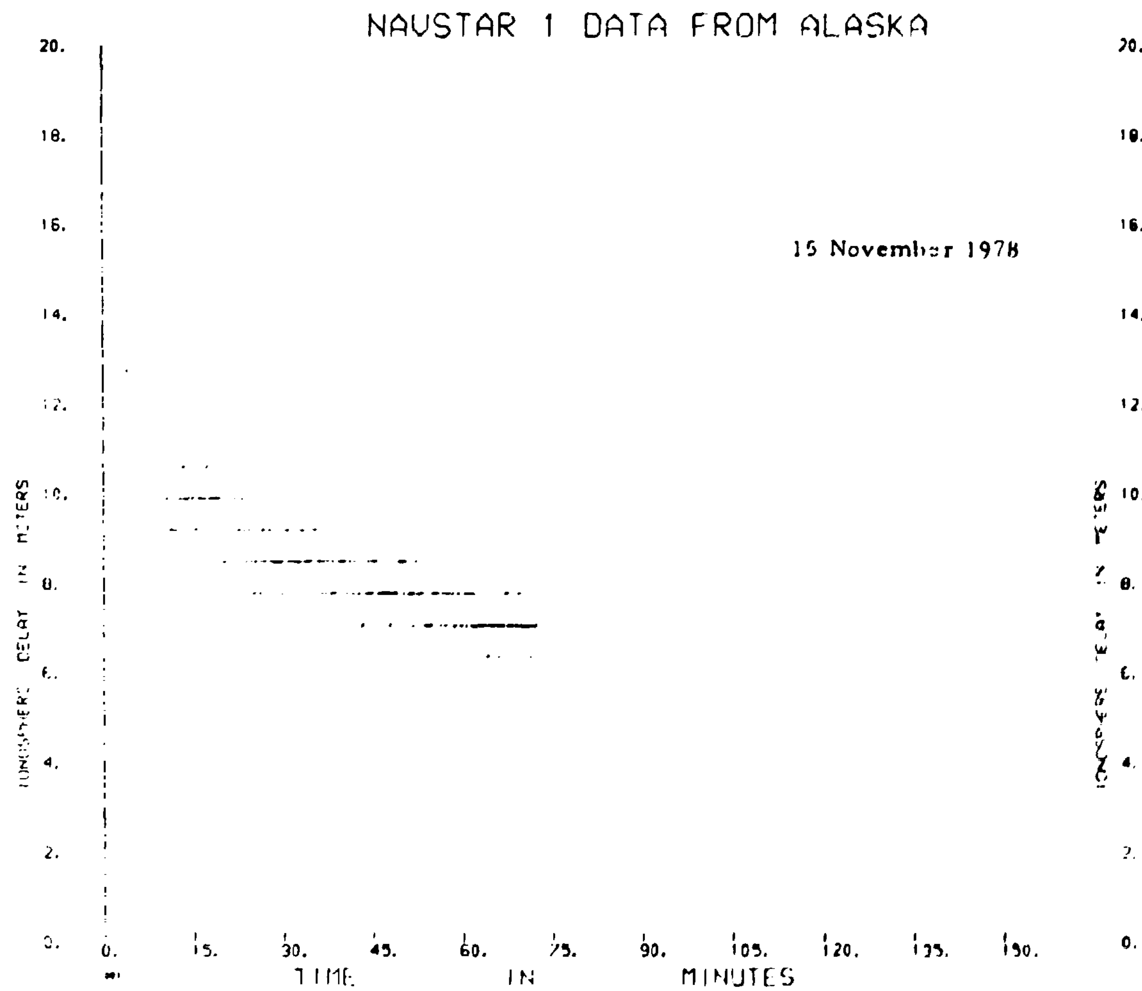


Fig. 9-8. Navstar 1 Data from Alaska: Two Frequency Method

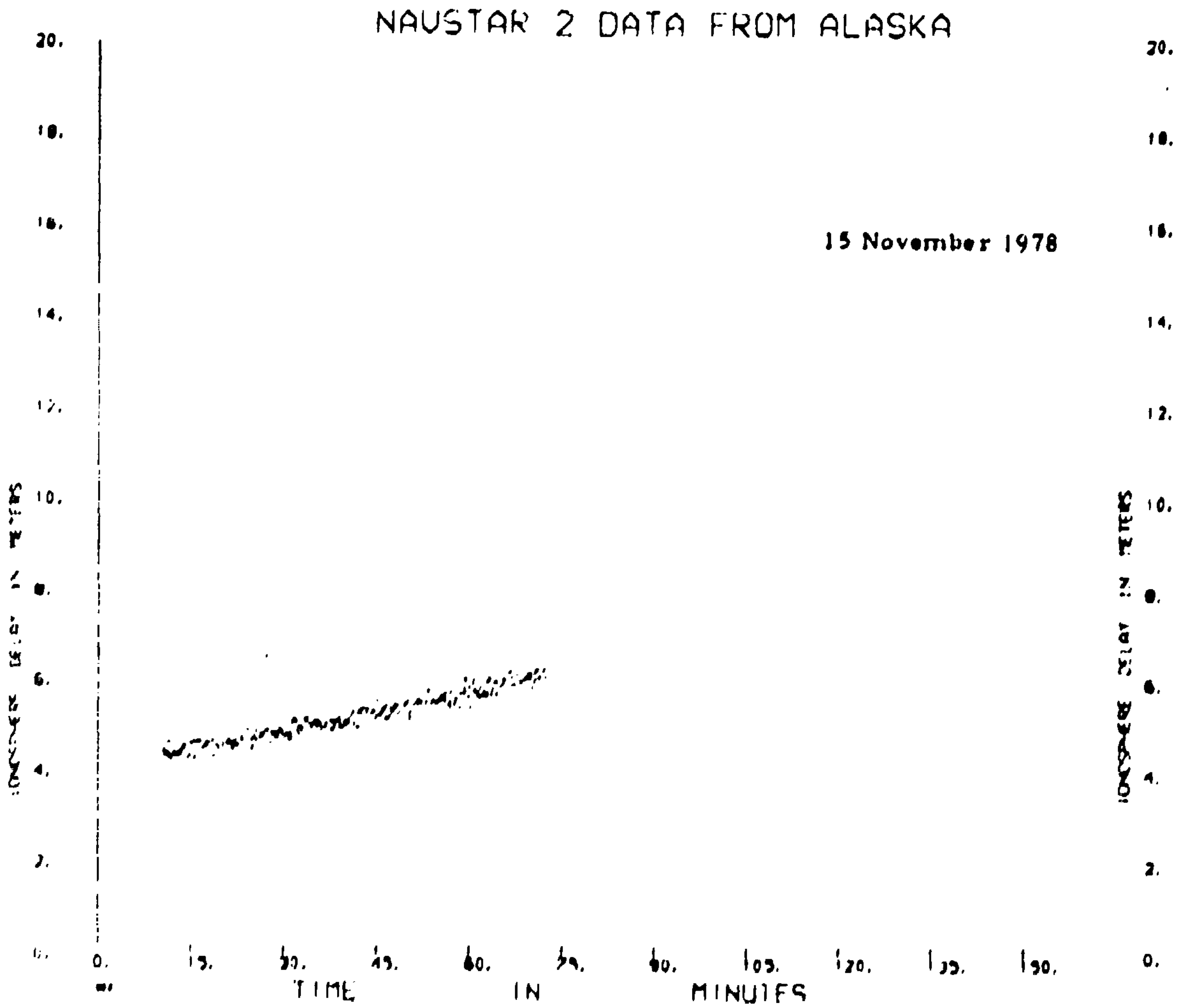


Fig. 9-9. Navstar 2 Data from Alaska: Group Delay Minus Phase Advance Method

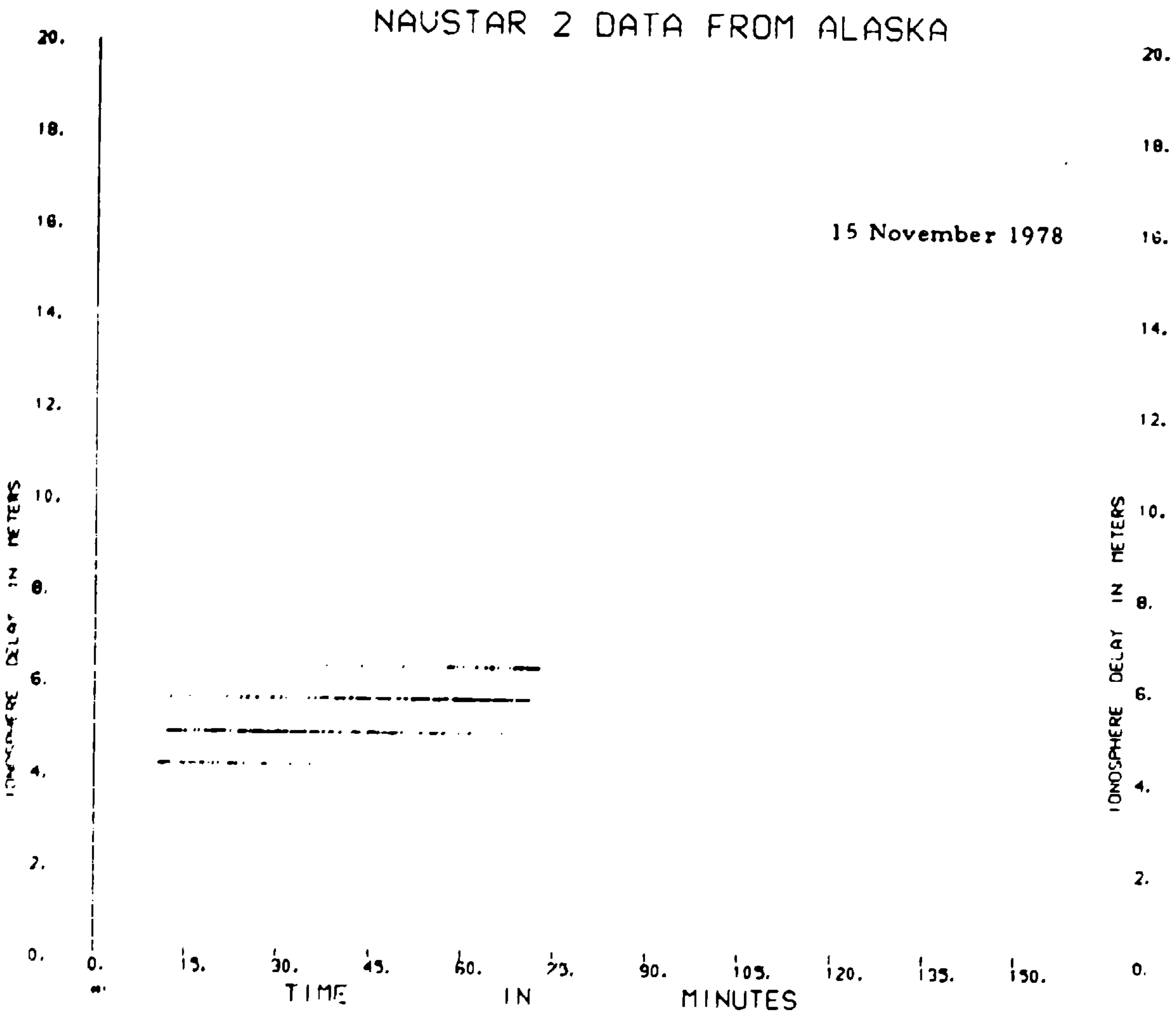


Fig. 9-10. Navstar 2 Data from Alaska: Two Frequency Method

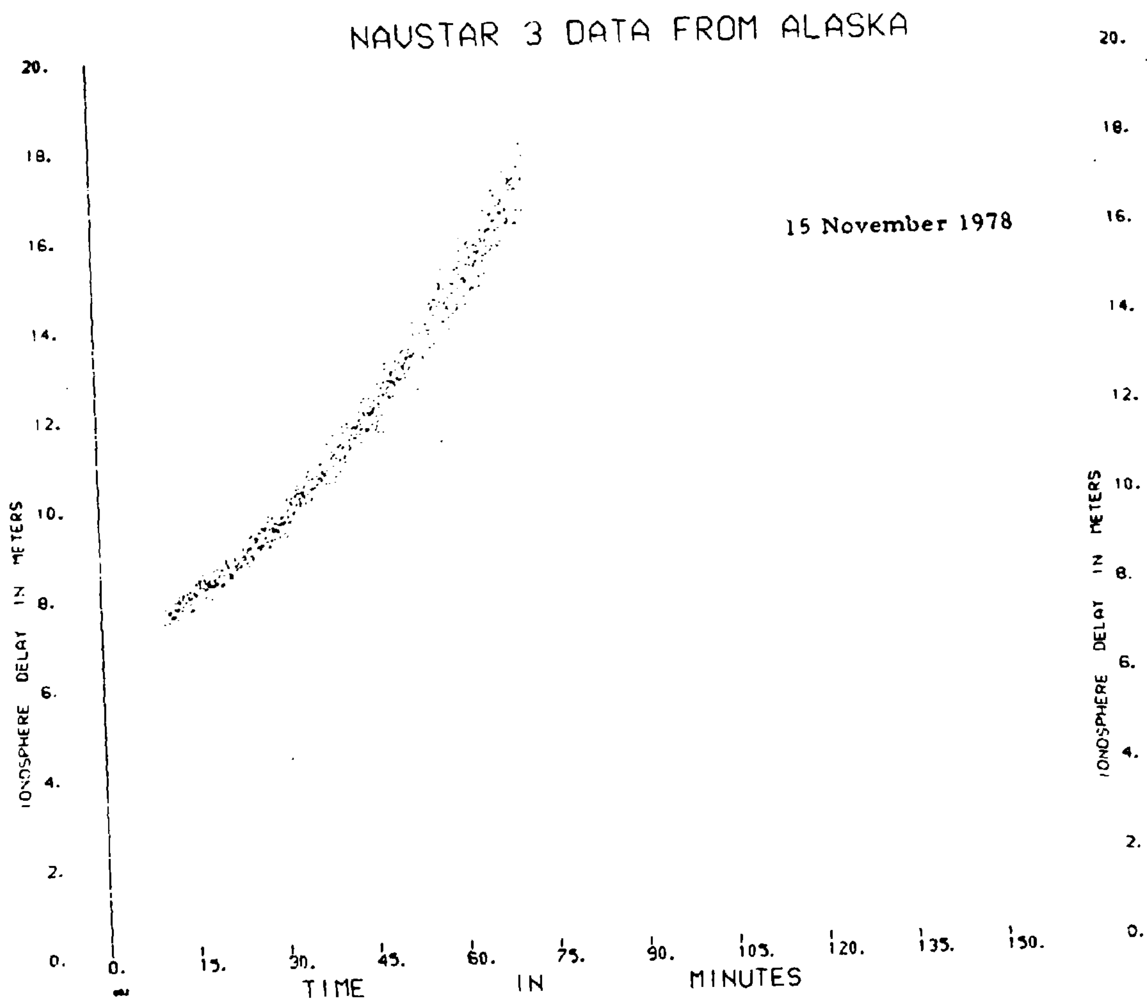


Fig. 9-11. Navstar 3 Data from Alaska: Group Delay Minus Phase Advance Method

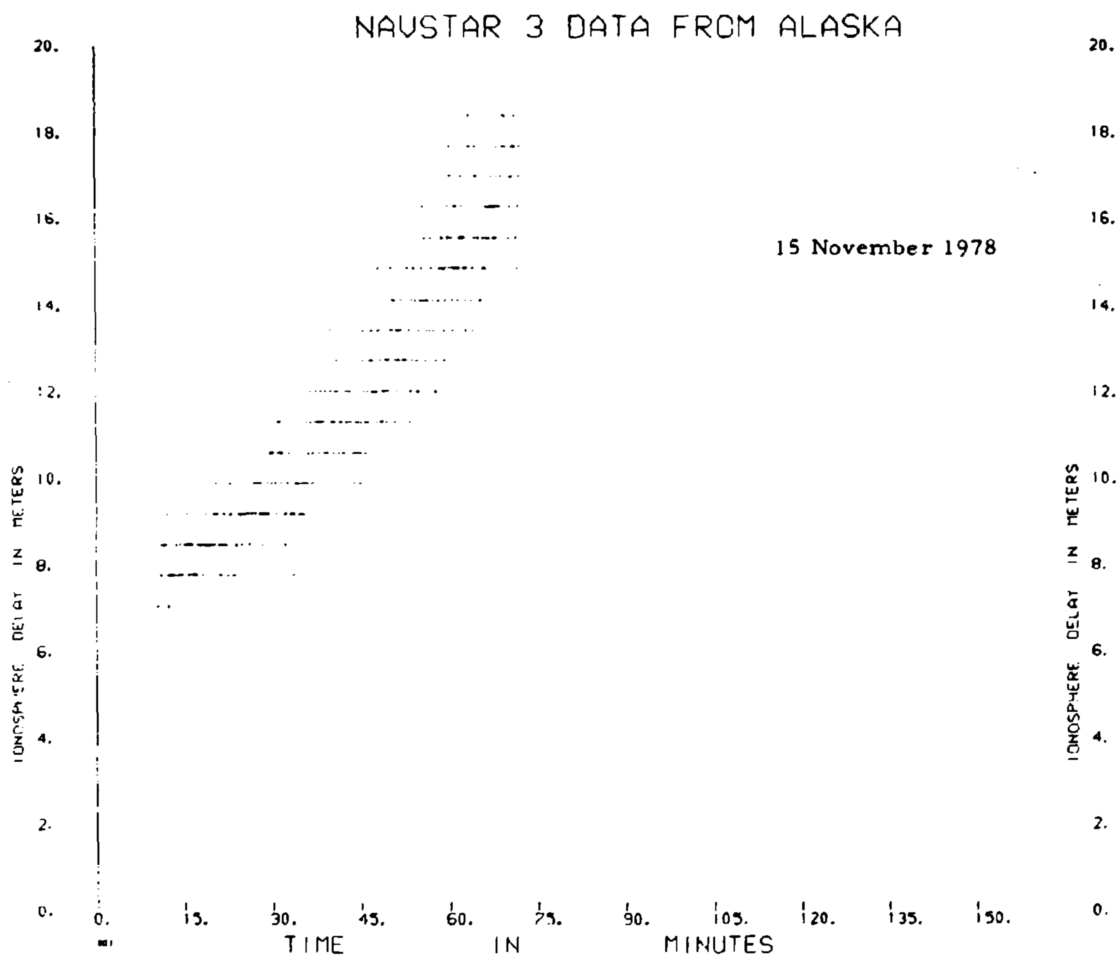


Fig. 9-12. Navstar 3 Data from Alaska: Two Frequency Method

In comparing the results of the two methods, the theoretically expected improvement in the accuracy of individual measurements from the group delay minus phase advance method over the two frequency method is clearly illustrated, but the correlation is generally good. An examination of the results using the group delay minus phase advance method shows that the scattering of the individual data points is on the order of a few tenths of a meter. By smoothing the data over a satellite pass, it should be possible to determine the ionospheric delay with a random error of less than one-tenth meter.

Gathering ionospheric delay data is an inherent capability of Navstar GPS. With a multiplicity of satellites and monitor stations, ionospheric measurements with considerable variability in direction and time can be made. As more satellites and tracking receivers become available, the opportunity will exist for obtaining large quantities of high-quality ionospheric data. Analysis of this data and its correlation with satellite position, time of day and year, and other factors will improve our understanding of the structure of the ionosphere.